Warm memories of the Shikoku Basin recorded within the Nankai inner accretionary wedge

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Paleothermal structure and tectonic evolution of an accretionary wedge is basic information for understanding subduction zone seismogenesis. To evaluate entire paleotemperature profile and evolutionary processes of the Nankai inner accretionary wedge, we performed vitrinite reflectance analysis and detrital zircon U-Pb age dating by using cuttings retrieved from the Integrated Ocean Drilling Program (IODP) Site C0002 located within the Kumano Basin and penetrates the inner accretionary wedge down to 3058.5 m below the seafloor (mbsf).
Both Ro values and the youngest detrital zircon U-Pb ages show a reversal between 2400-2600 mbsf, suggesting the existence of a thrust fault with sufficient displacement to offset both paleothermal structure and sediment age. Taking the reversal at 2400–2600 mbsf into consideration, apparent paleogeothermal gradients of 1700–2400 and 2600–3000 mbsf are calculated to be ~60 (~50–70)°C/km, assuming 1 million years of heating duration time. Geothermal gradient of ~60°C/km is significantly higher than the estimated modern geothermal gradient (~30–40°C/km; e.g. *Sugihara et al.*, 2014). For more precise estimation of paleogeothermal gradient, we collected effects of bedding inclination (subhorizontal to ~60°) and porosity reduction, and as a result, real paleogeothermal gradient of both hanging- and footwall of the presumed thrust fault at 2400–2600 mbsf is ~100°C/km. Such a large paleogeothermal gradient was probably obtained prior to subduction, reflecting large heat flux produced by young oceanic lithosphere and/or hydrothermal circulation within the Philippine Sea Plate. Our results suggest that large geothermal gradient of input sediments might have a potential to affect the up-dip limit of seismogenic zone.

Keywords: Vitrinite reflectance, Nankai Trough, accretionary prism, detrital U-Pb zircon age

Heterogeneous distribution of pelagic input sediments in the Japan Trench and its impact on seismic slip propagation

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Large coseismic slip reached to the Japan Trench caused catastrophic tsunami of the 2011 Tohoku Earthquake (e.g. Fujiwara et al., 2011; Ito et al., 2011; Kodaira et al., 2012). Coseismic slip propagation along the shallow portion of the plate boundary fault would be caused by low friction of smectite-rich pelagic clay consisting the fault, as suggested by researches on core samples taken by IODP Expedition 343 (JFAST) (Ujiie et al., 2013; Kameda et al., 2015; Moore et al., 2015). Recently, large heterogeneities in the thickness of incoming sediments are suggested by high-resolution seismic profiles perfomed by JAMSTEC. To reconcile whether the smectite-rich pelagic clay layer even exists in the area of thin incoming sediments, we analyzed lithologies and sedimentation rates of piston cores sampled from horst-graben structures of the Japan Trench.
All of coring sites are located in off-Sanriku area of the Japan Trench, north of the 2011 rupture area. Seven piston cores (PC01-07) were retrieved from seaward trench slope (PC05 and PC06), horst (PC03 and PC04), graben (PC01), and graben edge (PC02 and PC07) during the R/V Shinsei Maru KS-15-3 cruise. Sediment thickness estimated from seismic profiles are ~30-90 m at horst and seaward trench slope sites, and ~130-340 m at graben/graben edge sites, respectively. Visual core descriptions and successive density and magnetic susceptibility measurement by multi-sensor core logger (MSCL) on split core surfaces as well as X-ray CT imaging of whole-round cores have been performed at Kochi Core Center. Ages of tephra layers were estimated by comparing mineral assemblages and refractive indices of volcanic glasses to those of catalog values, and averaged sedimentation rates of each core were estimated.
Core lithologies are mainly diatomaceous clay/silty clay, with including tephra layers. Sedimentation rates of seaward trench slope, horst, graben, and graben edge are estimated to be ~20-40, ~5-20, ~45, ~1 cm/kyr, respectively. According to these sedimentation rates, sediments on seaward trench slope and horst sites have been deposited within the last 160-660 kyr. Our results suggest that entire pelagic sediments, including smectite-rich pelagic clay, have been removed by some reasons in the last 1 million years, where the thickness of incoming sediment is thin. The lack of smectite-rich pelagic clay may contribute to stop rupture propagation of 2011 Tohoku Earthquake at off-Sanriku Japan Trench. More understanding on sediment dynamics of deposition and erosion at trench outer rise is needed to link subduction input and megathrust earthquakes.

Structure of the incoming Pacific Plate subducting into the central part of the Japan Trench: Results from the repeated ocean bottom seismograph observations after the 2011 Tohoku-Oki earthquake

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Since the occurrence of the 2011 Mw 9.0 Tohoku-Oki earthquake, seismicity within the incoming/subducting Pacific plate has been active near the axis of the Japan Trench and trench-outer rise region. This active intra-plate seismicity, which includes several M7-class earthquakes, is characterized by normal-faulting focal mechanisms with trench-normal tensional axes. Seismicity observations using ocean bottom seismographs have been conducted repeatedly in the Japan Trench area after the 2011 earthquake. These passive seismicity observations would provide structure information of the incoming Pacific Plate subducting into the Japan Trench. Results from the traveltime tomography by using the data consisting of 120 stations and more than 8000 events in total show the seismic velocity changes in the incoming Pacific plate with the approach toward the trench axis. The P-wave velocities within the oceanic mantle reduced from 8.2-8.5 km/s at the 90 km east of the trench axis to 7.5-8.0 km/s beneath the trench axis. The P-wave velocity reduction is observed down to a depth of about 20 km below the oceanic Moho and might relate to the bending-related hydration/alteration of the oceanic plate prior to the subduction. We also investigated anisotropy and Q structures by using the OBS data. We will discuss the structures heterogeneities and their relationships with hydration/alteration of the Pacific plate in the trench-outer rise region by combining the results from these analyses.

Keywords: oceanic plate, outer rise

Refinement of scientific objectives, drill sites, and strategies for CHIKYU IODP proposal aimed at Bend-Fault Hydrology in the Old Incoming Plate (H-ODIN): Input from the London workshop

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Hydration due to plate bending-induced normal faults (bend-faults) in the region between the trench axis and outer rise (outer rise) has also drawn considerable attention (e.g., Grevemeyer et al., 2007; Fujie et al., 2013). Ideally, comparing subduction zones in several contrasting geodynamic states (e.g. Old plate vs Young plate, bend-faults being reactivated abyssal hill faults vs. newly formed horst-and-graben faults, etc.) is likely to be the most promising exploration approach to expand our knowledge of bend-fault hydration processes. In order to deepen our understanding of bend-fault hydration, an IODP pre-proposal: Bending fault hydrology of the Old Incoming Plate (H-ODIN) was developed. The IODP workshop, Bend-Fault Serpentinization, was held in London, 2016, sponsored by CHIKYU IODP Board, the UK-IODP, and ECORD. Horst-and-graben bend-fault structures are well developed in the northwestern Pacific subduction system. The Vp/Vs ratio is high at the outer rise area where bend-faults start to be developed (Fujie et al., 2013). Anomalously high heat flow valuesare found to be pervasively distributed in the off-Tohoku outer rise region (Yamano et al., 2014). The off-Tohoku region also provides a rare opportunity to study a place where the local stress state is likely to have changed significantly since the 2011 Tohoku Earthquake (Obana et al., 2011). Microseismic activity detected by OBS is considered to be related to actively deforming bend-faults (Obana et al., 2012, 2014). The questions on the nature of bend-fault hydration are classified into (1) Bend-fault material and structure, and (2) Bend-Fault Stress State and monitoring stress-state and fluid flow. The Japan Trench site seems best for understanding links between bend-induced hydration and the outer rise seismic cycle. (especially optimal now as we are in a rare phase between a giant megathrust event and its potential outer-rise doublet.). We will present more details in the presentation.

Keywords: Plate bending induced normal fault, Ocean Drilling Project, Earthquake, Water-carbon circulation

Current Status of Drilling-Related Plans to Study Consequences of Bend-Fault Serpentinization During Plate Bending offshore Nicaragua (Outcome from the June 2016 BFS/H-ODIN Workshop)

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During the last decade, multiple independent geophysical structure studies have revealed that plate bending-induced normal faults in outer rise regions around the world are associated with significant hydration. This bend-fault-linked hydration and Bend-Fault Serpentinization (BFS), with its associated physical and chemical changes, is one of the most significant geological discoveries of the last 15 years. It has the potential to reshape our understanding of Earth's deep water and carbon cycles, the ecology and evolution of species in deep-sea chemosynthetic environments, and even the fundamental mechanism by which slabs bend and unbend, thereby driving Plate Tectonics.

In-situ sampling of rocks and fluid tracers is a key tool to make further progress in our understanding of BFS, its implications for the hydrothermal system(s?) that can develop during plate bending, the extent of deep life within these systems, and the resulting chemical interactions between the downgoing plate and seawater. Offshore Nicaragua is a prime site for drilling-related study of this process because this is the place where ongoing BFS occurs in the the world's shallowest environment (2.9-3.4km water depth).

In June 2016 a group of interested scientists met at the IODP workshop "Bend-Fault Serpentinization, drilling proposals using the D/V *Chikyu*" to assess the best strategy for using scientific drilling to explore BFS at complementary sites at the Middle American Trench offshore Nicaragua and the Japan Trench. The drilling-oriented goals of the workshop were to refine scientific objectives, drill sites, and strategies for scientific drilling in the outer rise region in order to understand the nature of the bend-fault hydration in the incoming plate. We reached a provisional consensus on the best approaches to make the most rapid progress towards better understanding of this frontier area of Earth Science. The workshop discussed deep drilling plans, but it was felt that a staged approach is preferable for effective study of this system. A dual-mode drilling strategy was proposed: (Stage I), D/V JOIDES Resolution or D/V Chikyu drilling through the upper parts of the bend-fault system to better understand the chemistry and shallow fluids, fluid flow, and bend-fault-linked microbial ecosystems, and also assess and improve our current technologies and strategies for drilling through bend-faults, and (Stage II), a MoHole-type drilling strategy to sample an intact crustal and mantle section through 1km below the ~5.5km-deep crust-mantle boundary that has direct relevance to many M2M (MoHole) science objectives. This talk will briefly summarize the known constraints on BFS in this region, and then discuss the proposed strategy for future IODP investigation of this system. Any interested scientists are welcome to join the 'BFS Science Team' and help in the preparation of a full IODP proposal for Fall 2017.

Keywords: Bend-Fault Serpentinization, Outer Rise, Hydrothermal System, Scientific Drilling

Mantle Serpentinization near the Mariana Trench Constrained by Ocean Bottom Surface Wave Observations

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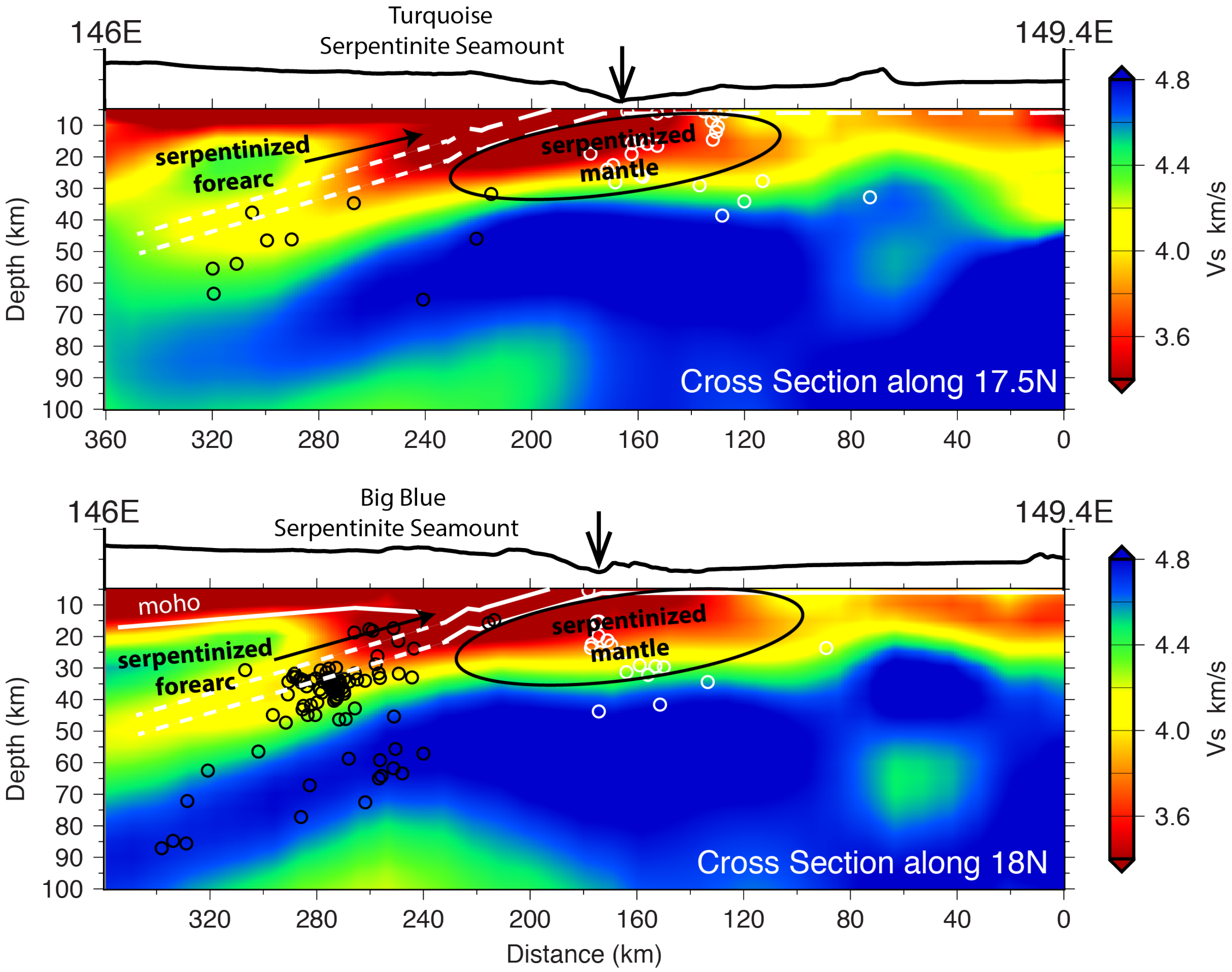
Although water is essential for many subduction processes, the water cycle at subduction zones remains poorly constrained. Serpentinization within the subducting and overriding plates have been observed at numerous subduction zones, with significant percentage variations. Widespread normal faulting on the incoming plate and serpentinite seamounts on the outer forearc in Mariana makes it an ideal place to study serpentinization of the incoming plate and the forearc mantle, and thus helps us to better understand the water budget of subduction zones. We investigate the shear wave structure of the crust and uppermost mantle across the Northern and Central Mariana trench using data collected by a temporary network involving both ocean bottom seismographs (OBSs) and land stations on the arc islands. Rayleigh wave phase velocities (10s –64s) are obtained with three different methods, including ambient noise tomography for short periods, Helmholtz tomography for the intermediate periods and two-plane-wave tomography for long periods. The dispersion curve obtained at each location is then inverted to SV velocities. Linear inversion results show low velocity anomalies around the trench axis, both within the incoming plate mantle and the forearc mantle wedge. The low velocity anomaly extends to about 30 km deep from the seafloor, well correlated with the 600-degree isotherm. The western and eastern boundaries of the anomalies are sharp, and have good correlation with the forearc serpentinite seamount locations and the incoming plate normal faulting earthquake distributions. The mantle shear velocity is as low as 3.2 km/s, indicating ~60% serpentinite component if the velocity reduction is purely caused by serpentinization. We will further apply a Bayesian Monte-Carlo algorithm to avoid the potential biases due to starting models and to better apply a priori constraints.

Keywords: Mantle Serpentinization, Water Budget, Surface Wave


Turquoise
Serpentinite Seamount
146E
149.4E
serpentinized
forearc
serpentinized
mantle
Depth (km)
Cross Section along 17.5N
Vs km/s
4.8
4.4
4.0
3.6
Big Blue
Serpentinite Seamount
moho
Cross Section along 18N
Distance (km)

Metasomatic records of lithosphere prior to subduction inferred from petit-spot

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The lithospheric mantle below oceanic regions is directly known only about largely restricted portions (mid-ocean ridges, back-arc spreading centers, and hotspots) where the ultramafic rocks are generally sampled from fracture zones and oceanic core complexes, or as xenolith entrained by magmas. The geochemical mantle has ever been previously recognized only by MORB and OIB as well. Monogenetic petit-spot volcano was first identified as magma squeezed upward at the flexed plate off the Japan Trench due to subduction. The magmas originate from the asthenosphere immediately under the plate, and erupt over a large eruption area (over 800 km of plate motion) but with low volumes of magma production each (Hirano et al., 2006). Such volcanoes have been reported from subduction zones worldwide (e.g., the Japan, Chile, Java, and Tonga trenches) (Hirano et al., 2008; 2013; 2016; Taneja et al., 2016). Xenoliths and xenocrysts entrained in petit-spot lavas provide direct information on lithosphere of subducting plate because the magma ascends along the concavely flexed lithosphere prior to the outer-rise along the trench. Here, we discuss the geochemical interactions between lithosphere and asthenosphere during ascending petit-spot melt using geochemistry of lava and xenoliths/xenocrysts from mantle.

Melt fractionations are required at the mid- or lower depth of lithosphere, given that bulk compositions clearly show fractionation trends of olivine in the absence of phenocrysts, in spite of raising lherzolitic xenoliths and xenocrystic olivines from deepest approximately 45 km (Yamamoto et al., 2015). Depth of the fractionation could be correspond to the σ_3 rotation from extensionally lower to upper compressional lithosphere due to the concave flexure prior to outer rise (Valentine & Hirano, 2010). The high levels of carbon dioxide derived by petit-spot magma recently explains the low seismic velocity and high electrical conductivity of oceanic asthenosphere as the source mantle. Experimentally equilibrated petit-spot melt, adopted 10 wt % CO_2 before emission (Okumura & Hirano, 2013), with harzburgite at the lower lithosphere implies the stagnation of ascending melt at the depth (Machida et al., 2017). Subducting lithosphere is likely metasomatized by the carbon-rich melt just prior to its subduction. The conventional theory about subducting lithosphere requires revision in light of recently obtained petit-spot data.

Transition of stress state of the oceanic lithosphere from shallower-half compression to shallower-half extension in outer rise

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1. Introduction
Recent studies revealed that hydration progresses in shallower part of the oceanic lithosphere from outer rise to the trench (within 100-200 km from the trench) [e.g., Contreras-Reyes *et al*., 2008, *JGR;* Fujie *et al* ., 2013, *GRL*]. In addition, high and variable heat anomalies were found in outer rise (within 150 km from the trench) [Yamano *et al*., 2014, *EPSL*]. These studies proposed that these phenomena are caused by water infiltration and circulation due to bending-related normal faulting and fracturing. The initiation and development of bending-related faulting depends on stress evolution of the oceanic lithosphere in outer rise. In addition, the stress state may control the easiness of the water infiltration. Thus, understanding the stress evolution of the oceanic lithosphere in outer rise will give us useful clues to clear the mechanism of these phenomena.

2. Origin of lithospheric stress
Stress in the oceanic lithosphere has history since it was generated at the oceanic ridge. Thermal stress due to cooling of the oceanic lithosphere is the main origin of stress in the oceanic lithosphere where is far away from the trench. Its stress state is characterized by shallower-half compression and deeper-half extension, and it well explains focal mechanism and seismicity rate of oceanic intraplate earthquakes [Sasajima and Ito, 2015, *SSJ fall-meeting*].
On the other hand, bending stress due to flexure in outer rise is shallower-half extension and deeper-half compression. Thus, transition of the stress state may occur around outer rise. In this study, we focus on this stress transition.

3. Simulating stress evolution
In order to clear the stress transition in outer rise, we modeled stress evolution of the oceanic lithosphere in the Lagrangian description since it was generated at the oceanic ridge. The target of this study is the Pacific plate around the Japan Trench (120-130 Ma). The model describes differential stress of 1D column of the oceanic lithosphere by time integration of elastic stress generation, brittle stress release, and ductile stress relaxation. Dominant components of elastic stress generation are thermal stress in young age and bending stress in outer rise.

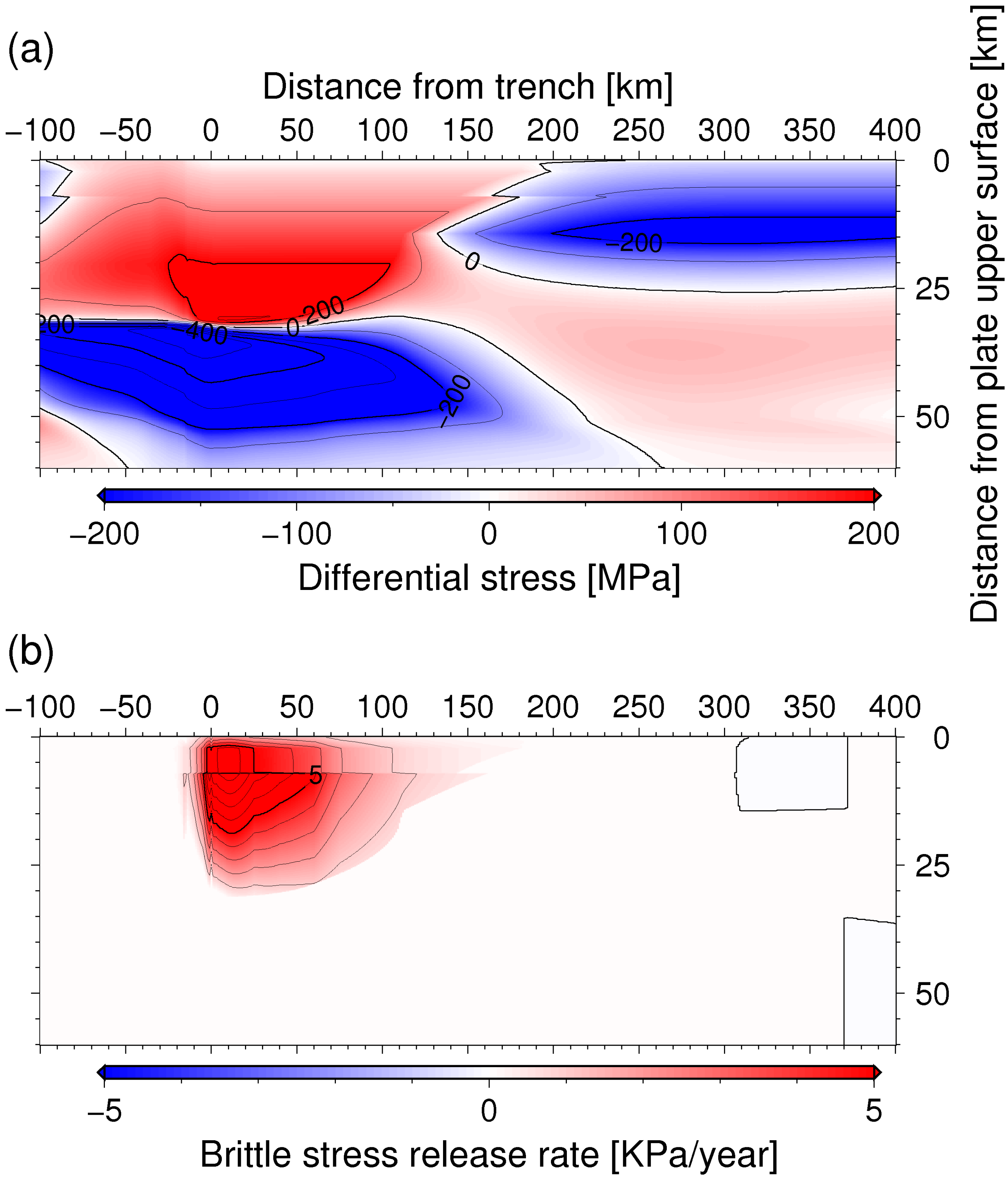
4. Results
Figure 1 (a) shows cross-section of modeled stress evolution of the oceanic lithosphere around the outer rise. Until the oceanic lithosphere reaches to 200 km from the trench, shallower-half stress state is compression due to residual thermal stress. The transition from compression to extension occurs during 125-175 km from the trench. The transition initiates at the shallower-most portion, and it expands to deeper portion. Figure 1 (b) shows modeled brittle stress release rates. Although bending deformation initiated at about 300 km from the trench, no normal faulting is expected during 175-300 km from the trench because of residual compressional stress. Thus, the thermal stress delays initiation of bending-related normal faulting.

5. Discussion

The horizontal location of the stress transition from compression to extension (125-175 km from trench) is consistent with the offshore-end (i.e., initiation) of observed hydration and heat-flow anomalies. It corresponds to the initiation of bending-related normal faulting, which may cause the water infiltration into the oceanic lithosphere. In addition, the stress transition from compression to extension likely promotes the water infiltration. Thus, we propose that the residual thermal stress is also important factor to control these phenomena in addition to the bending stress.

Figure 1. Cross section of the oceanic lithosphere. Horizontal axis indicates distance from the trench along the plate upper surface. The right side of figures is offshore. Vertical axis indicates distance from the plate upper surface along the depth direction. (a) Modeled differential stress (extension is positive (red)). (b) Modeled brittle stress release rates (normal faulting is positive (red)).

Keywords: Oceanic lithosphere, Thermal stress, Bending stress, Outer rise


(a)
Distance from trench [km]
–100 –50 0 50 100 150 200 250 300 350 400
0
25
50
Distance from plate upper surface [km]
–200
0
200
–400
0
200
–200
–200 –100 0 100 200
Differential stress [MPa]
(b)
–100 –50 0 50 100 150 200 250 300 350 400
0
25
50
5
–5 0 5
Brittle stress release rate [KPa/year]

Well-log characterization of hydration and dehydration processes in oceanic lithosphere: from mid-ocean ridges to subduction zones

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Hydration and dehydration of oceanic lithosphere are known to be central to understand geodynamics processes from mid-ocean ridges, to intraplate tectonics and magmatism, to seismogenesis and material cycles facilitated by subduction zones. Recent and proposed drilling efforts at various subduction zones particularly highlight the significance of lithosphere hydration by faults evolved in incoming plate (e.g. “Bend-fault serpentinization (BFS) and Bend-Fault Hydrology in Old Incoming Plate (H-ODIN)”). Although undertaking sub-meter to sub-centimeter scale observations on cored materials has been much desired approach in investigating the nature of lithosphere, drilling through faulted lithosphere and deeper crust has been, indeed, a challenging task throughout the history of scientific drilling, let alone obtaining continuous core materials with high to perfect recovery rates. Borehole informatics using downhole physical properties logging has been a known strategy to complement our understanding of drilled intervals with no core recovery in establishing the most optimal downhole lithostratigraphy model in hard rock drilled sites. Using case studies from the mid-ocean ridge and interaplate volcanic settings, we introduce that (1) downhole physical properties logging can also be utilized to further characterize lithosphere hydrogeology and associated alteration processes over time; and (2) microresistivity imagery logging profiles not only enable us to conduct detailed mapping of the orientation and distribution of hardly-recovered in situ fracture networks, but also to estimate void space abundances in crustal material and the determination of complex lithology-dependent void geometries. Together with petrological and rock magnetic evidences in terrestrial serpentinized lithosphere, we propose that sub-meter scale well-log characterization of drilled holes in the faulted lithosphere in incoming plate will enable us, at multiple scale, to delineate where seawater can permeate and serpentinization takes place, in turn, where microbes are possibly reside.

Keywords: oceanic lithosphere, hydration, serpentinization

The Permeability Structure of Oceanic Crust and Implications for Subduction Zone Hydrology

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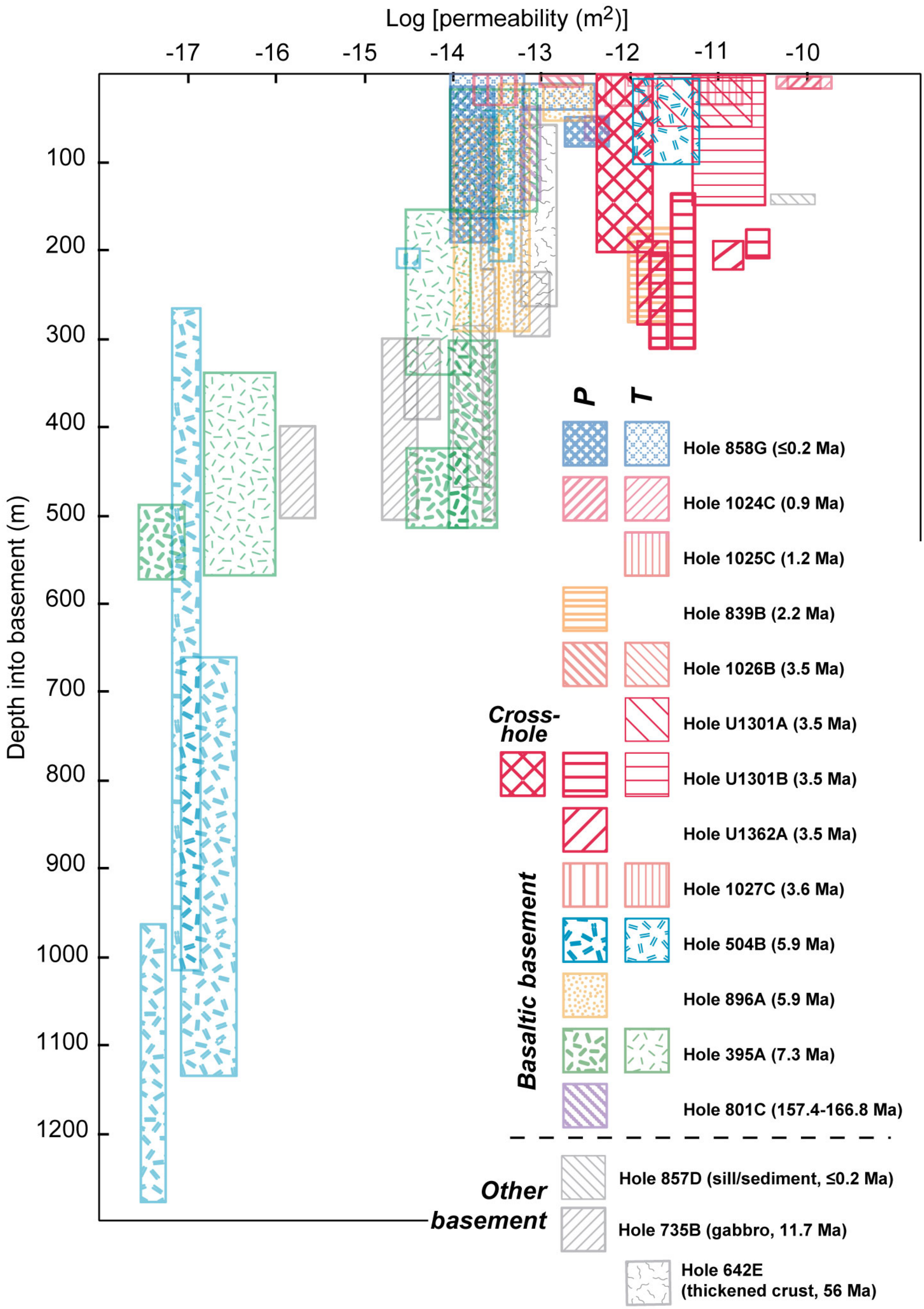
We review investigations of the permeability structure of the oceanic crust with a specific focus on implications for hydrogeological processes in incoming plates at subduction zones. Direct determinations of permeability require sampled materials or boreholes, so the cores and holes of DSDP, ODP, and IODP have been crucial to our understanding of ocean crustal permeability. Important techniques have included wireline logs, borehole temperature profiles, in-situ packer experiments, long-term records obtained with CORK sealed-hole hydrological observatories, and comparison of such in-situ results with constraints from numerical simulations.

Early DSDP packer measurements in 6-7 Ma off-axis settings suggested a simple layered permeability structure for upper oceanic basement in young ridge flanks, with a few hundred meters of permeable uppermost pillow lavas underlain by much less permeable deeper pillows and sheeted dikes. In ODP and IODP, there have been important new results on several fronts. Packer measurements and borehole flow permeability estimates have been completed in holes in oceanic crust spanning a wider range of age (0-12 Ma and 160 Ma; see attached figure). Permeability at larger spatial scales has also been estimated at some of these sites using other direct and indirect techniques including (a) analyses of the response of pressures recorded in sealed-hole CORK experiments to seafloor tidal loading and co-seismic deformation, and (b) numerical simulations of the nearly isothermal uppermost basement temperatures observed in paired ridge-flank CORK sites where there is considerable basement relief and large variation in sediment thickness. Combined results indicate the following: (1) Permeabilities of uppermost basement in sedimented young oceanic crust are very high. (2) Permeabilities of uppermost basement in young crust seem to decrease systematically as the crust ages, consistent with the evolution of seismic velocities in Layer 2A. (3) Permeabilities within oceanic crust seem to display a scale dependence, possibly as the result of the highly heterogeneous distribution of the permeable network within oceanic basement. (4) Lateral fluid fluxes are very high, but the inter-connected "effective porosity" that contributes to high permeability and fluxes is quite low; this has significant implications for fluid residence times and reactions with host rock depending on position within the network. (5) Lateral fluid flow directions in young crust must have a signficant component subparallel to the ridge axes and dominant tectonic structures, contrasting with earlier conceptual models configured as sections normal to structural strike.

Clearly, if relatively young oceanic crust is being subducted, as at Nankai, Central America, and Cascadia, its high permeability must be considered a signficant factor in the hydrology of the subducting slab (and, therefore, seismicity, volcanic activity, and related processes), even before accounting for the effects of plate-bending faults that, depending on geometry, may cross or reinforce large-scale lateral permeability provided by ridge-parallel tectonic fabric. Permeability data are much sparser in oceanic crust older than 10 Ma, but the few data points also indicate high permeability where fault zones or structural discontinuities are encountered. There is almost no data from deeper oceanic crust, and the nature and hydrologic significance of deep reflectors that penetrate the ocean crust and extend into the upper mantle remain to be determined. Plate-bending faults could augment permeability in subducting ocean crust of any age, and this effect could be particularly important when older, otherwise less permeable crust is subducted.

Keywords: Ocean crust permeability, Subduction zone hydrogeology, Plate-bending faults



Log [permeability (m2)]
-17
-16
-15
-14
-13
-12
-11
-10
Depth into basement (m)
100
200
300
400
500
600
700
800
900
1000
1100
1200
P
T
Cross-hole
Basaltic basement
Other basement
Hole 858G (≤0.2 Ma)
Hole 1024C (0.9 Ma)
Hole 1025C (1.2 Ma)
Hole 839B (2.2 Ma)
Hole 1026B (3.5 Ma)
Hole U1301A (3.5 Ma)
Hole U1301B (3.5 Ma)
Hole U1362A (3.5 Ma)
Hole 1027C (3.6 Ma)
Hole 504B (5.9 Ma)
Hole 896A (5.9 Ma)
Hole 395A (7.3 Ma)
Hole 801C (157.4-166.8 Ma)
Hole 857D (sill/sediment, ≤0.2 Ma)
Hole 735B (gabbro, 11.7 Ma)
Hole 642E
(thickened crust, 56 Ma)

A review of hydrothermal heat transport models explaining high heat-flow anomalies observed near the Japanese Islands

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Recent heat flow surveys have revealed that heat flow near the subduction zones is deviated from thermal models of the oceanic plate with the corresponding plate age. At the Nankai Trough and the Japan Trench, high heat flow anomalies are observed. We review physical characteristics of two distinct thermal models that have been proposed to explain the observed high heat flow anomalies.

Heat flow near the Muroto area of the Nankai Trough is more than twice that expected from plate models with the corresponding plate age 15 Ma (*Yamano et al.*, 2003), and that near the Kumano area (~150 km east of the Muroto area) is <50% higher than that expected from plate models with the corresponding plate age 20 Ma (*Kinoshita et al.*, 2008). To explain the high heat flow observed at the Muroto area, *Spinelli and Wang* (2008) constructed a thermal model including hydrothermal circulation. The uppermost ~500 m of the oceanic plate is highly permeable, and they assume that this part is also permeable after subduction. Hydrothermal heat transport within the aquifer upwells heat and decreases temperature, so that an isotherm of 150°C is shifted 50 km landward.

Heat flow within 150 km seaward of the Japan Trench is, on average, ~40% higher than that expected from plate thermal models with the corresponding plate age 135 Ma (*Yamano et al.*, 2008, 2014). Within this area, *Fujie et al.* (2013) have observed a high V_p/V_s layer at the uppermost part of the oceanic plate that is thickened toward the trench axis. Being inspired by this observation, *Kawada et al.* (2014) constructed a thermal model, in which a permeable aquifer is thickened toward the trench axis. Results show that hydrothermal circulation pumps up heat below the thickening aquifer to raise the heat flow above it. Its effect on the temperature structure of the subducted oceanic plate is minor.

We compare these two existing thermal models in a physical point of view. *Spinelli and Wang*'s (2008) model requires very high permeability, and we can call it the high-permeability-aquifer model. To account for the observed high heat flow at the Nankai Trough, preferred permeability is around 10^{-9} m^2 (nearly the upper bound of measured values; *Fisher*, 1998). This high permeability is required because heat and fluid are transported a long journey (several tens of kilometres) along the subducted aquifer. Thus, temperature reduction at depth is significant in this model. The efficiency of this hydrothermal heat transport is, at a first order, proportional to the aquifer permeability. Thus, according to this model, moderately high heat flow along the Kumano area of the Nankai Trough can be interpreted as having moderately high aquifer permeability (10^{-10} m^2, according to *Spinelli and Harris*, 2011). On the other hand, if this model is applied to the Japan Trench, where the oceanic plate of 135 Ma is subducting, the expected permeability is beyond the measured range.

Kawada et al.'s (2014) model involves the thickening of the aquifer, and we call it the aquifer-thickening model. This model, by contrast, requires moderate permeability. For example, to account for the high heat flow observed seaward of the Japan Trench, 10^{-12} m^2 is sufficient. Around this permeability value, its effect on the temperature structure of the subducted oceanic plate is minor. Interestingly, further increasing in the aquifer permeability results in little impact on the resulted heat flow at the seafloor. This is because the amount of heat pumped up by this mechanism, which mainly comes from the base of the thickening aquifer, is bounded by the thickening rate of the aquifer. The amount of heat pumped up by this mechanism is directly related to the thickening rate instead. It is unclear whether this model can be applied to the Nankai Trough, because there is no supporting information from structural observations at present.

Keywords: Nankai Trough, Japan Trench, Heat flow, Thermal model, Subduction zone

The nature of actively deforming Wharton Basin and its role in the subduction processes, offshore northern Sumatra

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The Wharton Basin is one of the most actively deforming ocean basins on Earth, which was confirmed by the occurrence of the 2012 Mw=8.6 strike-slip earthquake, along with its Mw=7.2 foreshock and Mw=8.2 aftershock. The seismological and geodetic data suggest that the Mw=8.6 earthquake ruptured several faults, oblique to each other, down to the base of the lithosphere. Using ultra-deep seismic reflection technique, we have imaged faults down to 45 km depth in this region, indicating that deformation in the Wharton Basin is indeed on the lithospheric scale. We find that the oceanic mantle there consists of two layers; an upper serpentinized layer where a large number of small earthquakes occur and a lower pristine layer where great earthquakes initiate and large stress drops occur. We also find that the boundary between these two layers corresponds to the second Benioff zone (Qin and Singh, 2015) of the Sumatra subduction. Using multibeam bathymetry and high-resolution seismic data, we have also imaged a large number of right-lateral shear zones, which along with the left-lateral, re-activated N-S fracture zones, form a conjugate system of faults accommodating ongoing deformation (Singh et al., 2017). The shear zones are formed by sets of en echelon normal faults, whose strike defines the direction of principal stress in the region. These shear zones and associated normal faults become much more pervasive in the outer rise region of the Sumatran trench, indicating a complex interaction between the bending stress and the principal compressive stress. The pattern of active faults and the occurrence of the great 2012 earthquakes suggest the possible creation of a nascent plate boundary between India and Australia in the northern Wharton Basin.

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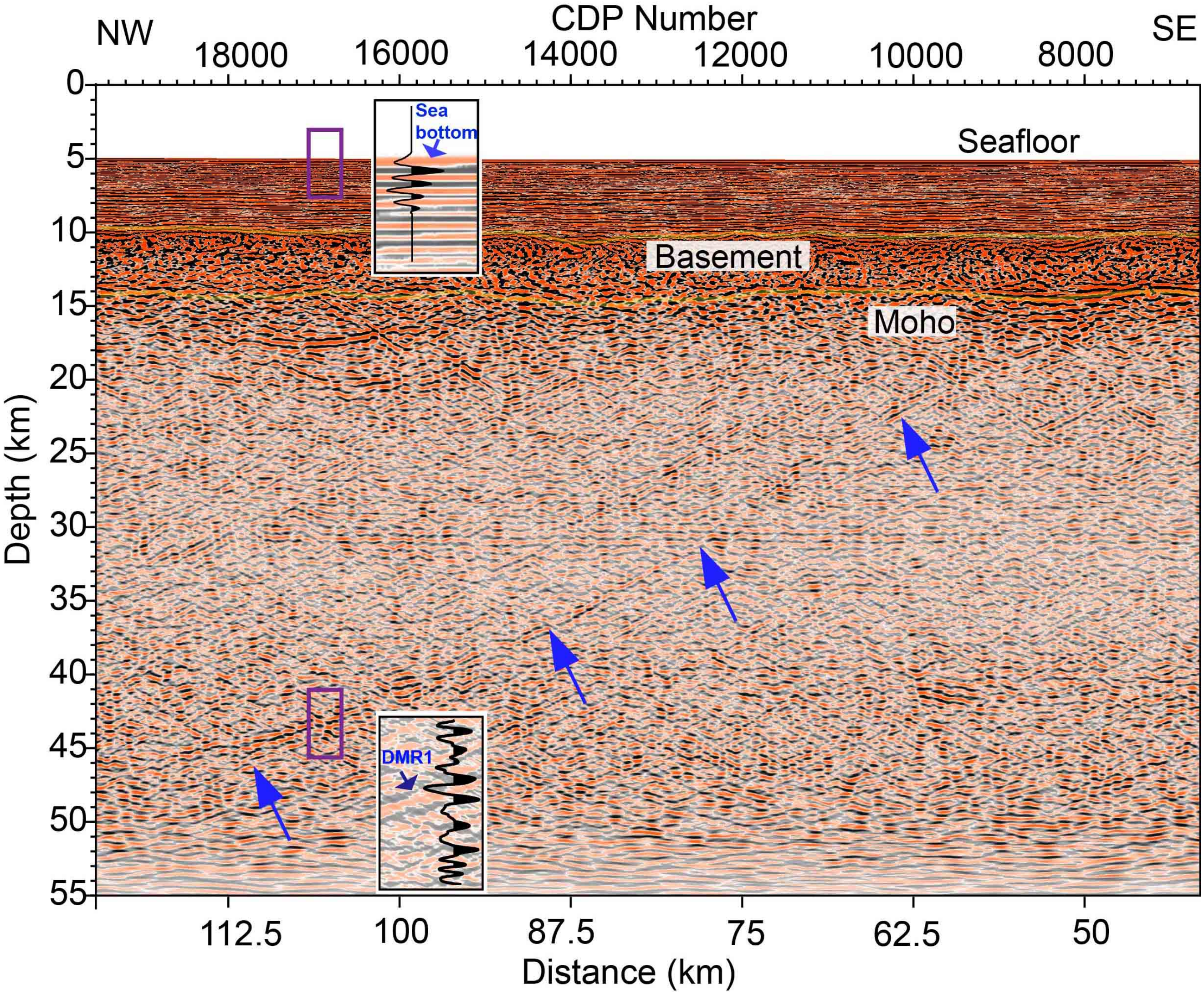
Keywords: outer rise, intraplate deformation, subduction, earthquakes, bend faults, shear zones


NW
CDP Number
SE
18000
16000
14000
12000
10000
8000
Sea bottom
Seafloor
Basement
Moho
DMR1
Depth (km)
0
5
10
15
20
25
30
35
40
45
50
55
112.5
100
87.5
75
62.5
50
Distance (km)